Low Temperature Hybrid Mars Ascent Vehicle Concept Development at MSFC

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A hybrid propulsion system is being developed as an option for the Mars Ascent Vehicle. There are several potential advantages to this system including low temperature survivability and higher performance. Both attributes could allow a hybrid system to be a single stage to orbit vehicle, with two firings of the motor. There are some processing and manufacturing issues with the fuel and the motor that must be understood in order for the advantages of a hybrid propulsion system to be realized. This paper discusses recent progress in the manufacturing of the hybrid fuel grains and subscale test firings conducted to characterize design features at MSFC.

I. Nomenclature

CTE	=	Coefficient of Thermal Expansion
ID	=	Inner diameter
JPL	=	Jet Propulsion Laboratory
MAV	=	Mars Ascent Vehicle
MON	=	Mixed Oxides of Nitrogen
MSFC	=	Marshall Space Flight Center
NASA	=	National Aeronautics and Space Administration
OD	=	Outer diameter
SFT	=	Solid fuel torch
SP1	=	Paraffin based fuel
SP7	=	Wax based fuel
SPG	=	Space Propulsion Group

II. Introduction

Returning samples from Mars has been studied by NASA for decades. The current Mars Sample Return mission concepts have multiple rockets launched from the earth, where the first rocket delivers a caching rover to collect and package the Martian soil samples. That descent vehicle/rover, Mars 2020, is currently being assembled at JPL. Another rocket sends the Mars Ascent Vehicle (MAV) to Mars. It lands, collects the prepacked samples and launches the samples to Mars orbit. A third rocket sends an orbiter that rendezvous with the samples in orbit, and brings them

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back to Earth. Our tasks have been focused on the Mars Ascent Vehicle. The MAV is subjected to many challenges including the harsh Mars environment and the requirement for a two burn trajectory, one to get off the planet and another to circularize the orbit. To meet these challenges, recent studies have led to the investigation of a hybrid rocket solution. This technology has been under development for several years[1], [2], [3], [4],[5],[6],[7]. This paper discusses some of the work going on at MSFC to understand how to process the fuel and test firings completed to characterize internal design features.

III. Fuel Processing

The baseline design for the Mars Ascent Vehicle (MAV), coming out of the Point of Departure review in December 2016[8] was a Mixed Oxides of Nitrogen (MON) oxidizer and SP7, a wax-based fuel. SP7 was developed by Space Propulsion Group (SPG) to handle the temperature extremes expected on Mars[9]. A low survival temperature is desired for the MAV to minimize the energy required to keep the propulsion system warm, freeing up energy for other purposes. Thermal cycling testing has been performed on representative samples, and the fuel survived with minimal to no cracking; however, there was some debonding of the fuel to case[10]. Flexible, cold temperature insulation materials are needed and this is an area of future work.

In the planning for the FY2017 round of full scale hot fire testing with vendors, it was decided to have MSFC update the SP7 processing and provide the fuel grains for the tests of record at the two vendors. SPG and Whittinghill Aerospace have been doing testing in Butte, Montana and Mojave, California, respectively[1]. This paper will discuss the process development from early development melting (Figure 1) to large mixers, and from hockey pucks to monolithic grains (Figure 2) and the recommended grain configuration.

Figure 1 Early Melting attempts in a small, commercially available, deep fryer.

Figure 2 Full-scale Monolithic Fuel Grain.

The fuel grain manufacturing process was initiated at Space Propulsion Group. Their casting concept was based on technology developed for their SP1, paraffin-based fuel. The technique needed to be applicable to both the SP7 fuel and SP7 fuel with additives. That process was working but still needed some development work to move to full scale. Due to a potential upcoming down select between competing hybrid rocket concepts, MSFC was asked to develop a process to manufacture the grains that would be independent of the two competitors. The MSFC grains would be used in the test firings where the data would be used for the down select. Around that same time, the requirement for additive loading was dropped.

The process development at MSFC has been a collection of trial and error attempts. First attempts working with the material were melting the SP7 ingredients in a deep fryer (See Figure 1). The process development was limited by the amount of time required to take the SP7 ingredients from their ambient state to a fully molten material at ~110 C (230 F) as well as keeping it below the point where the SP7 starts to oxidize and lose volatiles at ~121 C (250 F). This kept testing cycles to approximately one casting a day, with the grain diameter being set by stainless steel mixing pots used as casting vessels.

Early on, there were many attempts with and without mandrels to produce the cylindrical port in the fuel grain. Multiple configurations were tried for the mandrel. Solid metal mandrel sections lead to cracking as the SP7 went from liquid to solid sections, as the SP7 shrinks by ~20% volume during the phase change. If the outside edges cooled/solidified before the core, this would lead to cracks and voids as the center solidifies. Various soft materials were used to wrap the mandrel to allow shrinkage (oil absorbent pads, quilting batting, pool noodles, etc.). It was difficult to find a material to seal the mandrel consistently (oven bags were eventually found to work). If/when the molten SP7 got past the mandrel barrier, the mandrel could not be removed without damaging the grain (Fig. 3).

Figure 3 Early grain casting showing a mandrel design and grain cracking and voids.

In order to heat the amount of liquid SP7 to develop the test grains, a commercial wax melter was purchased. This allowed 110 kg (250 lbm) of wax to be melted at once; however it takes ~5 days to go from ambient material to a fully molten mix. With larger amounts of molten SP7 material available, different concepts could be tried. To further improve the casting process, a programmable oven was also acquired. This allowed the cooldown to be regulated. Thermocouples were purchased, and temperature in the grains during cooldown was measured. These grains gave valuable information about the casting process but were not used for testing due to the embedded thermocouple wires.

Commercially available cake pans were bought to cast in. The first cake pans were ~5 cm (2 inch) tall/20 cm (8 inch) diameter and when ambient cooled normally produced crack free grains (Fig 4). This was scaled up to ~10 cm (4 inch) tall/30 cm (12 inch) diameter pans which inconsistently cracked or survived cooling in ambient conditions. This scale pan supported the test grain diameters. It is believed that the short length over diameter configuration leads to one dimensional cooling. Therefore, increasing the length leads to cracking during cooldown. There is still a percentage of grains that survived cooldown intact, but crack when machined. This suggests that ambient cooled grains harbor residual stresses.

Figure 4 Pie pan grain.

Based on the temperature measurements and observations of the cracked grains, several theories were suggested as to how to make large, crack free grains. The concepts were based on controlling the cool down process. Two of the early concepts pursued were thermal mass and end cooler (see Figure 5). The thermal mass concept consisted of preheated outer bucket that was filled with sand around the casting pan (~30 cm (12 inch) tall, 20 cm (8 inch) diameter). The sand and bucket were preheated, filled with liquid SP7 and allowed to slowly cool down based on the thermal mass. There was some success with that approach at the initial scale. The end cooler approach was to try to get the solidification in one direction by insulating all the sides but one. In the limited testing with a 30 cm (12 inch) tall, 30 cm (12 inch) diameter grain, the end cooler configuration led to some massive cracks. The thought was the containers allowed some non-one direction cooling of the SP7 and that additional heat loss led to the outer surface cooling and cracks and voids as the interior cooled. Perhaps it could have worked with better control over boundary conditions.

A simple, unverified thermal textbook model indicated it could take over 53 days for a flight sized monolithic grain to cool in this manner, with heat loss from one end. Therefore, the one directional axial cooling technique (end cooler) was abandoned.

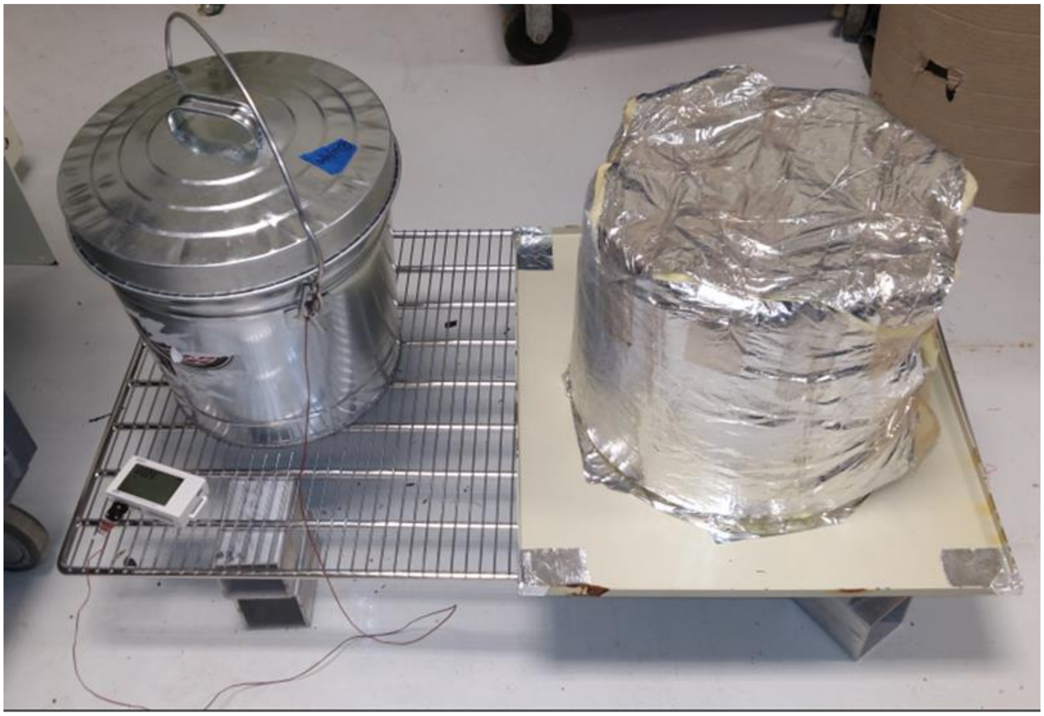

Figure 5: Thermal mass (left) and End cooler (right) concepts.

An experimental test series was initiated with the following three variables: mandrel vs no mandrel, cast height and cool down rate of the oven. This series incorporated the idea of the thermal mass concept, with the cool down controlled by the oven, not the thermal mass. The upper and lower cooling rates were tested with mixed results. Fuel grains with mandrels typically cracked. Some of the other shorter grains were successful, but longer grains cracked. Eventually it was decided that a mandrel did not need to be used, since if it was successfully cast, it would still need to be machined to the final dimensions. The test series was overcome by events and results, and tests at the middle temperature range were not completed. Although the test series was not finished, its results demonstrated the value of slowing the cool-down rate for constructing larger grains and the justification for abandoning the mandrel.

The need to start producing grains for hotfire testing forced the process down selection to the wafer grain concepts. Many thin grains would be made using cake pans. The top and bottom would then be milled flat, and the inner diameter (ID) and outer diameter (OD) would be machined using a waterjet. Subsequently, machining the OD was performed with a lathe instead of the waterjet due to the inability to hold tolerance with the lack of residual material remaining on the OD. These machined wafers were then stacked and cut to the right length to make the grain (see Figure 6). After the first set was shipped to a vendor and comments/feedback was given, the process was modified so that all the surfaces were machined on the lathe. This process change eliminated one tooling process and gave smooth finishes on all surfaces.

The grain wafers could also affect the stress in the grain during vibration loading and thermal cycling. An initial review of vibration loading suggests segmentation could beneficially reduce the stresses of vibration, provided the wafers stay in good contact. The thermal cycling issue may also have benefits from unbonded fuel wafers in that the temperature range experienced on Mars [10] would be large. The coefficient of thermal expansion differences between the possible case materials and the SP7 can be an order of magnitude. This thermal loading scenario was investigated at in a more detailed structural analysis. This is an area that will require future work.

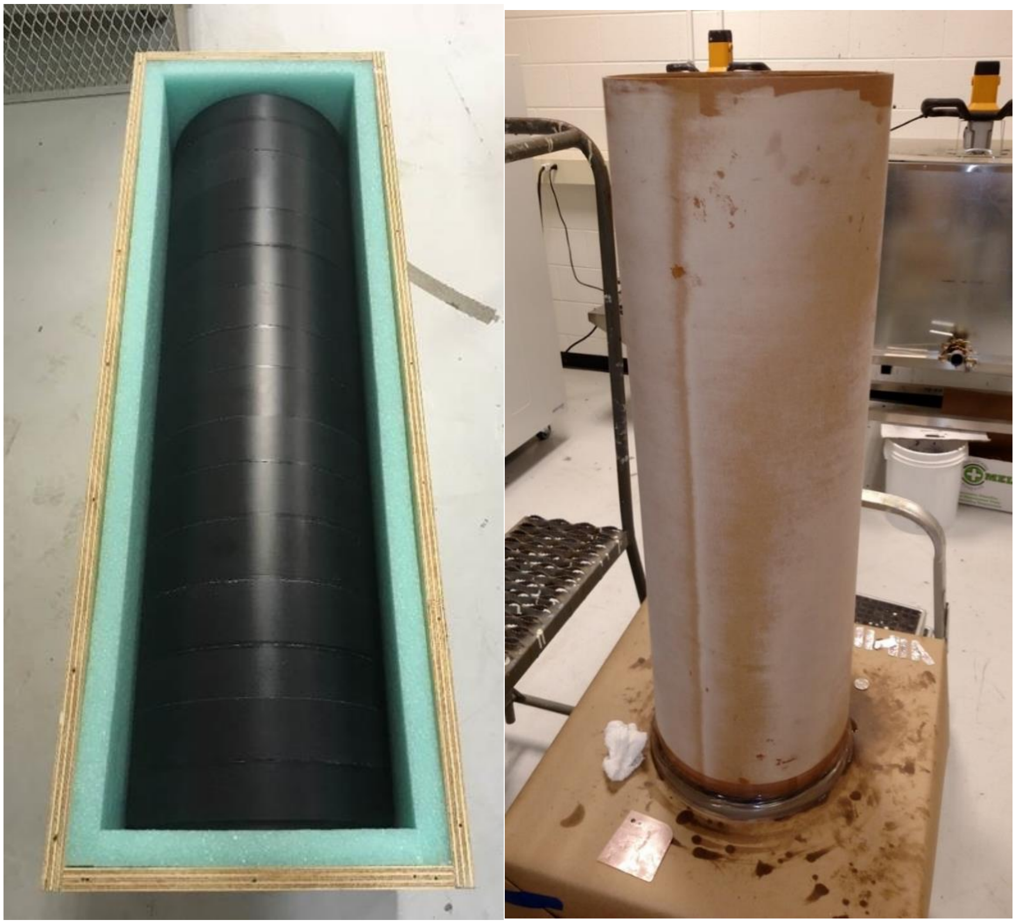

Figure 6 a) Multi-segment fuel grain b) multi-segmented fuel grain inside a phenolic tube.

A. Grain Configuration Leading Candidate

Considerations of these results, facility capabilities, and fuel grain system implications led to the following characteristics as the team's recommended implementation for future testing and flight design:

- Grain formed as a stack of segments, with no bonding between segments. This helps with the CTE issue as well as the vibration issue.

- Grain segments cooled in the oven with specified cooling rate. This allows thicker grain segments than the original cake-pan sized ones, and proved more effective than the thermal mass or one-dimensional cooling concepts. Based on reduced cracking during cooling, this process lowers the residual stress in the grains.

- Cast full cylinders and machine in the central port afterwards. This eliminates the need for a mandrel, which eliminates cracking and allows the ID to be machined to the proper dimensions.

Additional steps and experiments getting to this recommended configuration are described in the remaining sections.

B. Grain Bonding

One vendor wanted the grains separate for processing at their facility. The other vendor wanted the grains bonded inside a phenolic tube. The bonding in the tube was a learning process of its own. The tubes were ordered to strict tolerances and due to their flexibility when empty were hard to measure before SP7 fuel segments were bonded inside. The OD was sanded down after the bonding. The IDs were not smooth and required sanding before bonding. Phenolic tubes were brought down to the shop and grains were machined to fit into the tube. The shop normally has the exterior doors open for airflow and the temperature is cooler than the lab where bonding occurs, which has several ovens and a wax melter. Two times grains that fit in the machine shop did not fit in the lab. This required rework or cooling of the grain segments in a cooler part of the building.

The bonding process consisted of stacking the grain segments vertically on a flat plate, applying adhesive to the grain OD and tube ID and then sliding the tube over the stack (See Figure 7). The adhesive used was a two part, room temperature curing epoxy with low viscosity with a short pot life.

Figure 7 Preparing the grain and tube for bonding.

On the first grain, the forward and aft grain interfaces were tight, but the interior grain segment's OD was smaller. The grain and phenolic tube were buttered and the tube slide on the grain. After the adhesive cured, there were large voids found between the grain and the tube due to the adhesive settling before curing. There was a concern that if the fuel grains were unsupported during motor operation, the grains could crack. Corrective action included drilling holes in the tube on two ends of the voids, injecting adhesive in the lower hole, and pulling a vacuum from the higher hole. That process reduced the larger voids down to much smaller voids, which were deemed to be acceptable.

A lesson learned was to keep a wet bead on the top grain OD to tube interface, so it could flow down into the voids. Sometimes the bottom of the tube would have adhesive run out and various tapes were used to seal that interface. After the epoxy cured, additional sanding was required to clean up the adhesive that leaked out.

C. Oven Cooling

Additional improvements were made to the grain processing. Casting pans were preheated in the oven and liquid SP7 pumped into the pans. The grains were subjected to a controlled rate of cooling. Oven cooling the grains over the span of several days has allowed for crack free generation of grains up to ~16 inches tall and 12 inches in diameter. Dissection of several sample grains have not indicated any interior voids or cracks. The first two sets of grains sent to the vendors used the ambient cooled process; after that only oven cooled grains were sent to the test vendors. There were some limitations as to the size of the pieces that could be lathed due to the weight of the grain being held by three point chucks. However, this issue was worked out as the move to monolithic grains was made. This will be described in the next section.

Minor changes to the process have yielded oven cooled grains that cracked during processing. In order to keep the in-house manufactured sheet metal fabricated casting pans round at the open end and allow more of the grain to be useful, a plywood rounding ring was employed in the top of the pan. Holes were drilled in the plywood to allow air flow. Grains using those plywood rounding rings cracked during cooling. It is postulated plywood rounding rings affected the grain cool down process and that caused this cracking. The plywood rounding rings are no longer used.

D. Monolithic grain

One of the objectives of the casting process was to manufacture a monolithic grain. A large pan was made in which the grain could be cast. It had a metal ring welded at the top to keep the pan circular. Using a modified cooling process in the oven, a full length grain was cast and cooled. The exterior of the grain looked good after it was removed from the pan. Due to the size, the previously used lathes, located in the same facility as the oven, could not be employed. It was transported to another machine shop. During transport, the top of the grain broke off. Upon further review of the grain, there was a dome shaped void in the top of the grain. The outside of the grain had cooled and solidified. As the inside cooled down and shrunk as it changed from liquid to solid, it pulled away from the solidified exterior surface. The remaining bottom section was still large enough to machine into the shorter of the full scale configurations (See Figure 2). A second monolithic grain was cast using the same process. It's believed that it has the same dome void in the top end, but it hasn't been nondestructively evaluated or broken open to confirm that. There have been suggestions on how to produce a monolithic grain without the dome void; however, they haven't been pursued due to the belief that the multi-segment grain may be the better option for the MAV hybrid design.

Figure 8 Monolithic grain after fracture, dome void. Upside down from cooling position.

The monolithic fuel grain was requested for testing at one of the vendors. It was modified to meet their configuration and shipped to the vendor's facility. It was shipped during a cold snap and the grain sat outside in ~-30 C (-22 F) weather on an unheated trailer over the weekend before delivery to the vendor. Upon arrival at the vendor's facility, it was removed from the shipping container and put on chocks in ~20 C (68 F) work space. The grain looked good with the exception of some minor possible scratches/cracks on a feature. However, approximately two hours later, the grain fractured (see figure 8).

Figure 9 Fractured Monolithic Grain After Thermal Shock.

Upon further review and a thermal and structural analysis, it was determined that the monolithic grain was subjected to a large temperature change, combined with the high CTE of the SP7, resulting in the grain cracking. The grain exceeded the recommended temperature maximum ramp rate of 10.8 C/hr from reference 10. Further shipping to that vendor during winter included provisions to keep the grain from experiencing extreme temperature swings and potential gradients worse than what would be expected for the Mars mission.

Additional testing was done concurrently to confirm the theory. One previous observation was that a grain segment conditioned in a -19 C (-2 F) freezer shattered when removed and left on the table. That process was recreated with similar results. This confirms that the SP7 should not be exposed to large thermal gradients. However, it can still be operated over a wide range of temperatures under natural cycle times. The driver for the thermal gradient was determined to be entry, descent and landing on Mars in the winter. The SP7 is expected to survive the gradients from that worst case condition.

Figure 10 shows the remnant cut off top of a large oven cured grain after it had been stored in the freezer at -18 C (-2F) for at least several weeks. There is no center hole, and the only machining it was subjected to was to remove the lower segment that was used for fuel grains. A video camera was used for visual and audio evidence, and the grain was set on the table in the lab directly after being removed from the freezer. The lab was 23 C (73F). There were several pops right away in the first couple minutes. One crack broke thru the wafer and several others were clearly visible along the top surface. The surface cracks are highlighted in Figure 10, and the through crack is shown in Figure 11. It should be noted that this segment of fuel had a substantial amount of surface roughness since it was the top of a grain that is usually discarded or machined off. However, it confirmed what had been seen in Ref. 11: if the temperature gradient exceeds 10.8 C/hr, the SP7 will crack in this size scale (25-30 cm(10-12 inches)).

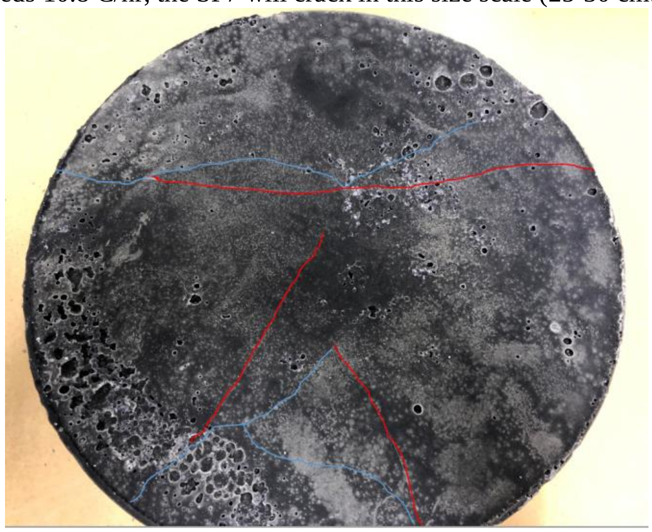

Figure 10 Cracks after removal from the freezer @ 4min 8 sec, blue observed during removal, red after pops.

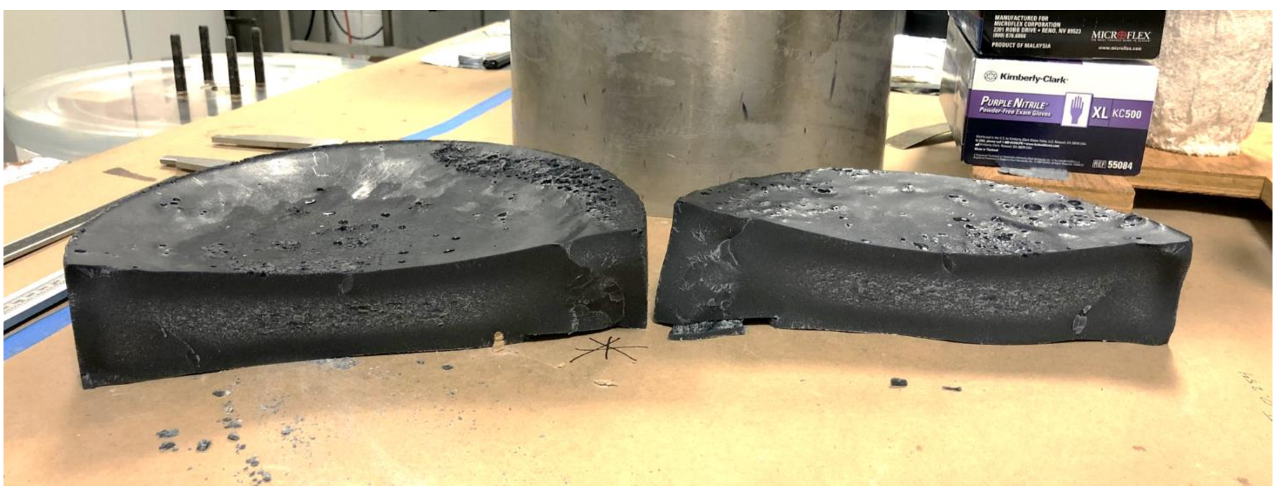

Figure 11 Freezer grain after warmup.

Figure 12 Small Solid fuel torch castings(upper left), ambient cooled grains(middle left) and some larger oven cooled grains(the rest).

Also ongoing is research into the residual stress in the grains. This may be done experimentally and supported with analysis, but it's not a trivial problem due to the SP7 from liquid to solid phase change volume reduction.

IV. Solid fuel tests

After the thermal testing was complete[10], it was noted that the Coefficient of Thermal Expansion (CTE) effects on the grain would be the worst in the longest dimensions. It was proposed that instead of stress relief flaps used in solid rocket motors, a segmented grain would be used. The reduced inert mass would be beneficial to the overall MAV design.

A. Structural analysis

Structural analysis was performed with the limited SP7 properties available[11]. The analysis included looking at CTE stress effects on temperature swings with different length grain segments.

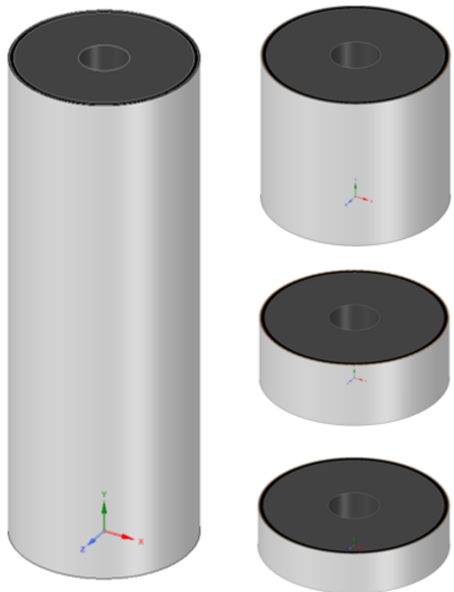

Figure 13 Configurations used in the grain stress analysis.

That analysis indicated:

1) Reducing the segment length of the SP7 propellant has theoretically shown to have a correlative impact on the peak stresses seen within the propellant and along the propellant boundary.
2) The most significant improvement is realized in the axial stress direction. Tensile stresses, specifically, see the most improvement.
3) Compressive stresses in the axial direction are shown to increase, however, this is likely not to become a critical issue on the structure given the extremely small magnitude of the axially compressive stresses.
4) Radial and circumferential stresses were also reduced but by a lower amount.

E. Solid Fuel Testing

The encouraging findings of the structural analysis led to an evaluation of how a multi-segmented motor would perform in an actual hybrid motor. It was postulated that the grain interfaces might change how the grain's surface regressed. Therefore, a test program was developed based on the readily available solid fuel torch hardware[12], using gaseous oxygen as the oxidizer instead of MON3 at MSFC. A firing of the Solid Fuel Torch motor can be seen in Figure 14.

Figure 14 Solid Fuel Torch Firing

The tests had identical total length grains with the first one being stacked wafers bonded together, the second one being representative of monolithic (3 segments without adhesive between the wafers), and the third one being made up of stacked wafers (no adhesive between the segments). All fuel grains had adhesive between the fuel and the phenolic tube. The same oxidizer flow rate and burn time were requested and delivered for each of the three tests[13].

The results of the testing objectives are most easily seen visually. The first test evaluated the configuration with the epoxy between the fuel segments. The results are displayed in Figure 15, as increased erosion can clearly be seen between the segments.

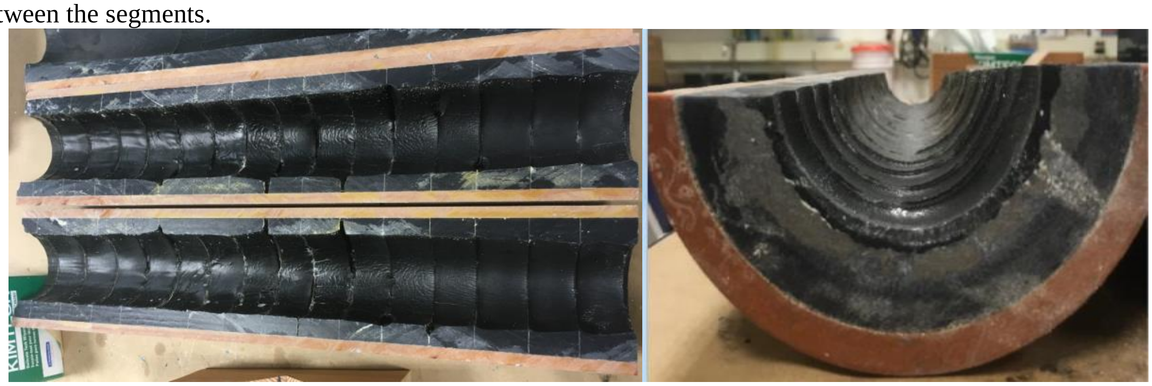

Figure 15 SFT Test 1, unbonded grain configuration

The monolithic configuration, Figure 16, shows that the grain regressed evenly down the port. There was no intentional adhesive in between the segments.

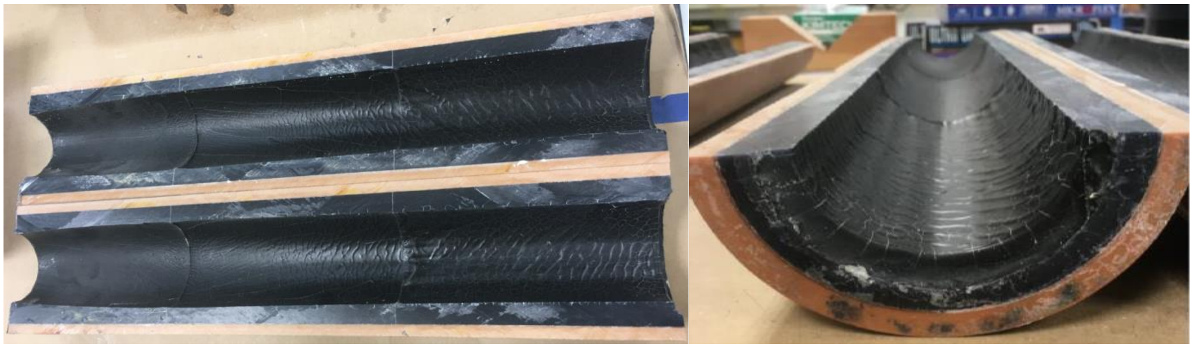
Figure 16 Test 2, Monolithic configuration

Test 3 had an unbonded fuel grain configuration, see Figure 17. The regression was observed to be even throughout the grain length, with no noticeable difference at the joints.


Figure 17 Test 3, Unbonded grain

The three solid fuel torch tests run in this study proved useful in a variety of manners. The study utilized different fuel grain manufacturing techniques to study the effects of the fuel grain bond lines. The most evident effect of the different fuel configurations is the varying fuel regression along the fuel grain segment bond lines. Test 1, bonded segments, showed the greatest change in fuel regression along the bond lines, with areas burning through to the case. The effects of the localized high fuel regression are not necessarily evident in the thrust or pressure traces. However, this testing made it clear that multi-segmented fuel grains can be used for this configuration and that they should not be bonded, or at least bonded with the epoxy used in this testing. Additionally, this testing contributed to the study of the performance of the hybrid motor utilizing gaseous oxygen as the oxidizer and SP7 as the fuel, providing the first regression rate information.

There are other configurations/conditions that could be evaluated with the solid fuel torch. In the MAV mission fabrication, fuel grains will be assembled into the motor at room temperature. The MAV is currently planned to be warmed to -20C for launch. That temperature delta indicates there may be some axial gapping between the segments. Understanding the effect of that gapping or adding a flexible material that won't affect regression rate is needed. There is potential for the solid fuel torch to be used in the future to reduce the risk of thermally induced gaps in the fuel grain.

V. Conclusion

MSFC has developed processes for manufacturing SP7 based grains in the scale needed for the MAV hybrid propulsion system option (~28 cm). Ten full scale fuel grains have been delivered and tested at subcontractors. Manufacturing these grains was more difficult than originally anticipated. SP7, being a wax based fuel, is tricky to manufacture because it shrinks by about 20% during the liquid to solid phase transition. SP7 also has a large CTE that makes motor design for the large MAV temperature swings more delicate. Solutions have been found for some of the issues, but others still need to be overcome.

Solid fuel torch testing was used as an indication of how the larger scale grains would behave during hotfire testing. It was an inexpensive, relatively fast way to determine if segmented fuel grains would cause problems such as uneven burning. It was found that the segmented grains without adhesive in between the layers performed as well as the larger (as close to monolythic as possible at the time) in terms of regression rate uniformity. The grains with adhesive regressed more rapidly at the segment boundaries, creating a non-uniform regression rate. The solid fuel torch tests were a good predictor of the outcome of the full scale tests.

Acknowledgments

The authors would like to thank all the people who helped in this effort: Mark Black, Sadie Boyle, Hoss Burtts, John Dankanich, Aaron Flinchum, Randy Handley, Kelly Lynch, Heath Martin, MSFC test area, Tommy Reed, Luke Scharber, Dan Stephens, Zac Strimbu, Bobby Taylor, Will Till, and Tom Zoladz.

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